# $CO_2$ fluid flow modeling to derive the time scales of lateral fluid migration

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# Overview

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- Methodology
- Fluid Flow Modeling
  - Hydraulic Diffusivity
  - Darcy’s Law of Fluid Flow
- Permeability Classifications
- Conclusions

# Introduction

- This study quantifies 1st order approximations for the time scales of $CO_2$ lateral migration through a 1.0 km representative volume of rock

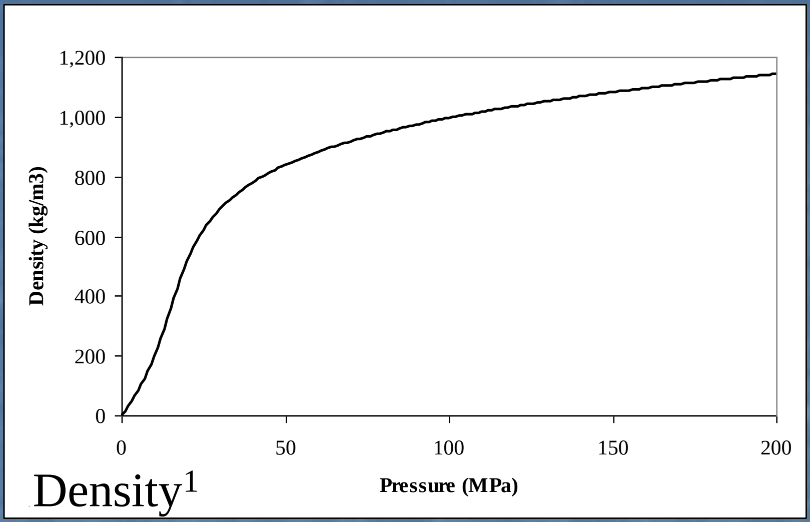
- Characterization and classification of subsurface strata into geologic-based subdivisions

- U.S. Geological Survey geologic-based assessment methodology for fully probabilistic determination of the storage capacity of geologic formations for $CO_2$ sequestration (Brennan, et al., 2010; Burruss et al., 2009)

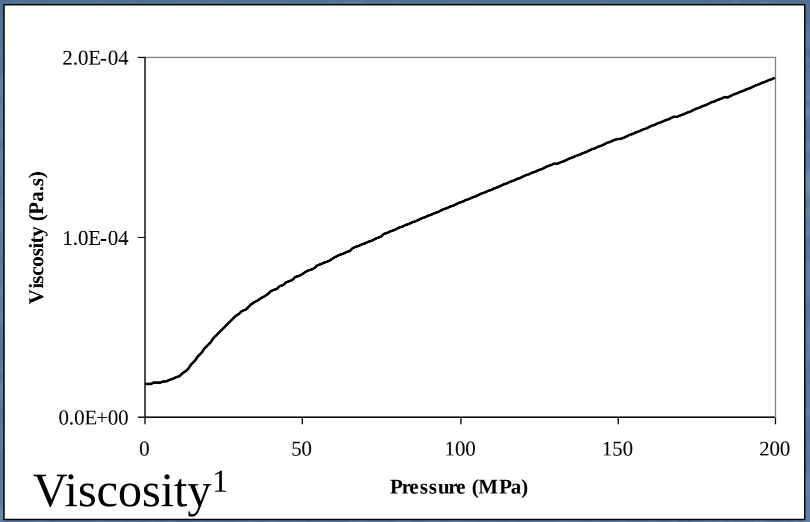
# Permeability Classifications

| Classification | Permeability Range (Darcy) |
|---|---|
| Class I | Class I ≥ 1.0 D |
| Class II | 1.0 D ≥ Class II ≥1.0 mD |
| Class III | Class III ≤ 1.0 mD |

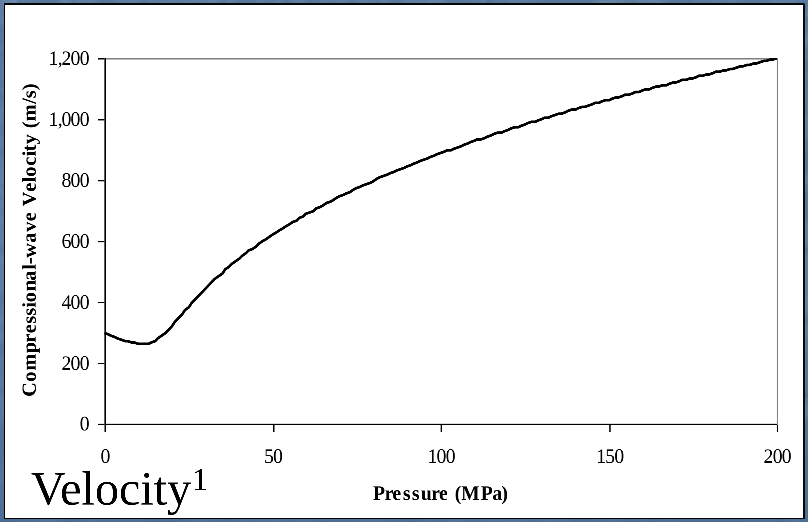
# Thermophysical Properties of $CO_2$



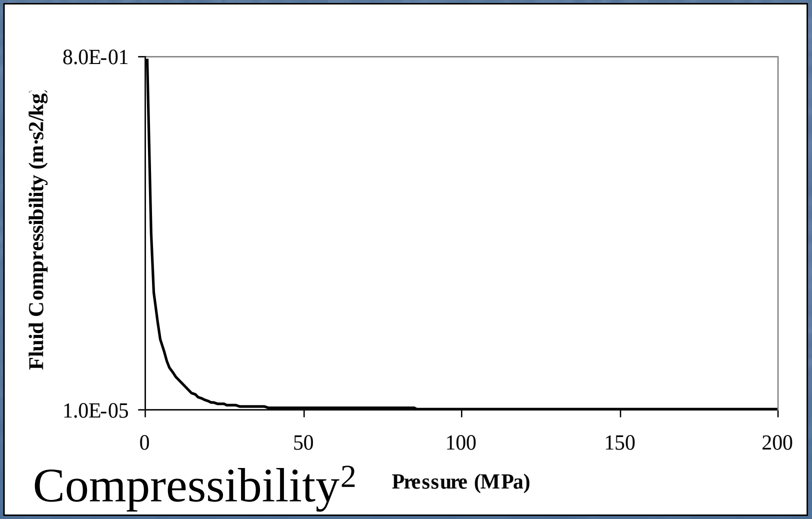

Density[1]




Viscosity[1]




Velocity[1]




Compressibility[2]

[1] Data from Lemmon et al. (2011)

[2] Calculated from $Vp=[(4/3u+k)/p]^{½}$

# Appraoch

- $CO_2$ sequestration is targeted for injection and subsurface containment at depths from approximately 3,000 to 13,000 ft

- Midpoint is 8,000 ft
  - Normally geopressured region with 100,000 ppm TDS:
  - 0.465 psi/ft (Schlumberger, 2011)
  - Generalized geothermal gradient for shallow crustal rocks:
  - 1.65 °F/100ft (Sheriff, 1994)
  - Average surface temperature: 68 F

- Pressure and temperature conditions of an “average” sedimentary formation at 8,000 ft: 25.5 MPa and 200 F

# Fluid Flow Modeling

Hydraulic Diffusivity time scale, $\tau_{hd}$ , in years:

$$\tau_{hd} = \frac{L^2}{2\alpha} \qquad \text{where} \qquad \alpha = \frac{k}{\eta\left(\frac{\phi\beta}{1-\phi} + \phi\beta_f\right)}$$

Darcy's Law time scale, $\tau_D$, in years:

$$\tau_D = \frac{\eta\phi L^2}{k\Delta P} \qquad \text{from} \qquad Q = \frac{kA}{\eta}\frac{\Delta P}{L} \qquad \text{and} \qquad v = \frac{k\Delta P}{\eta\phi L}$$

# Flow Modeling Parameters

| | Property | Variable | Value | Units |
|---|---|---|---|---|
| $CO_2$ Properties | Viscosity | $\eta$ | 5.00E-05 | kg/m·s |
| | Fluid Density | $\rho$ | 628.06 | kg/m$^3$ |
| | Fluid Compressibility | $\beta_f$ | 1.66E-02 | MPa$^{-1}$ |
| | Compressional-wave Velocity | $V_p$ | 390.28 | m/s |
| Rock Properties | Bulk Compressibility | $\beta$ | 3.10E-02 | MPa$^{-1}$ |
| | Lateral Distance | $L$ | 1.00 | km |
| | Fractional Porosity | $\phi$ | varies | dimensionless |
| | Matrix Permeability | $k$ | varies | D |
| | Darcy Pressure Differential | $\Delta P$ | 25.5 | MPa |

Fluid Properties

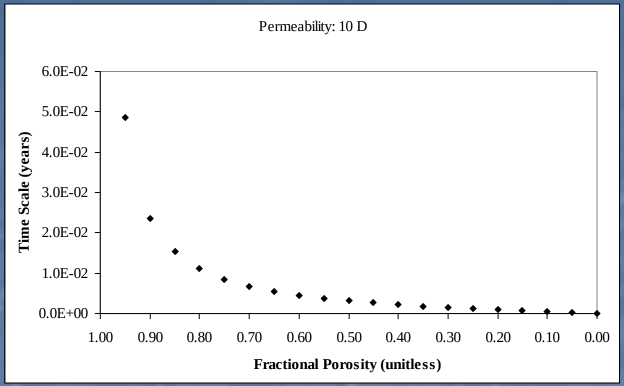
- At 25.5 MPa and 200 F

Rock Properties

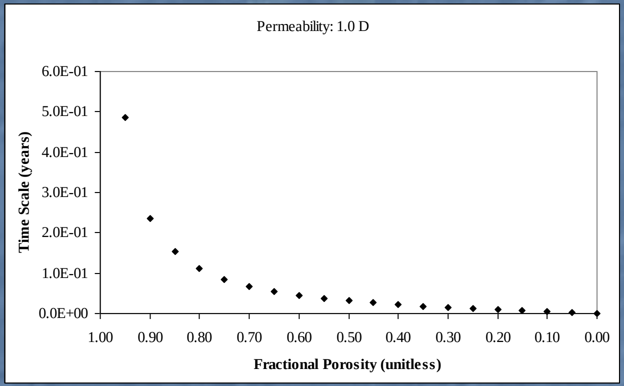
- Fractional porosity varies from 0.05 to 0.95
- Matrix permeability varies from 1.00E+01 to 1.00E-12 D

# Hydraulic Diffusivity Results

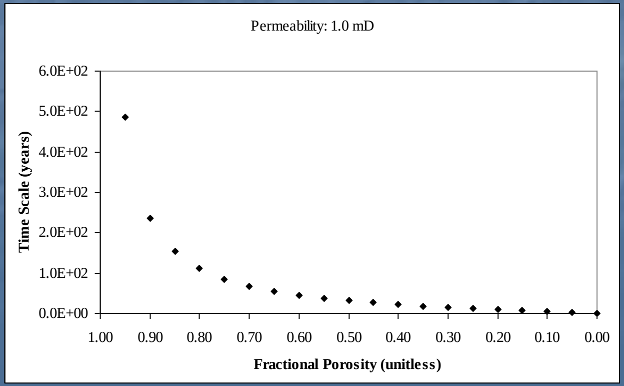
10.0 D



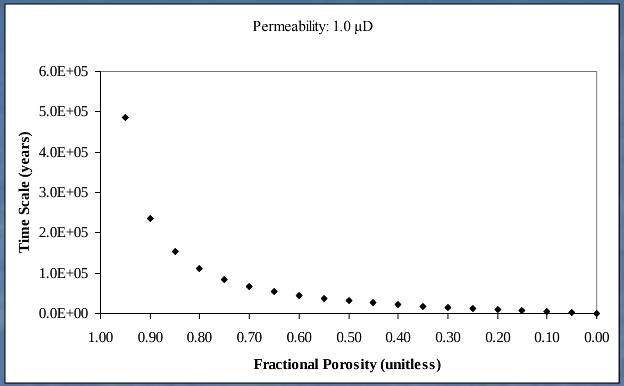

1.0 D



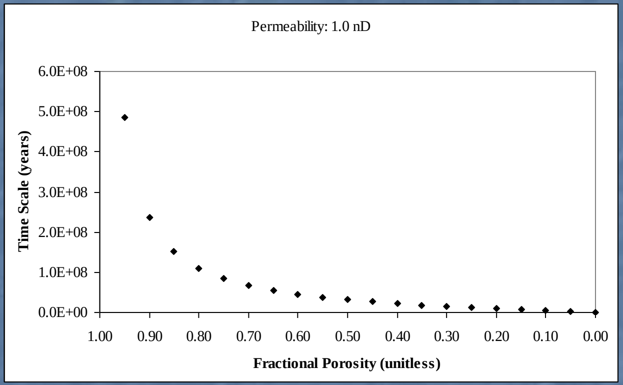

1.0 mD



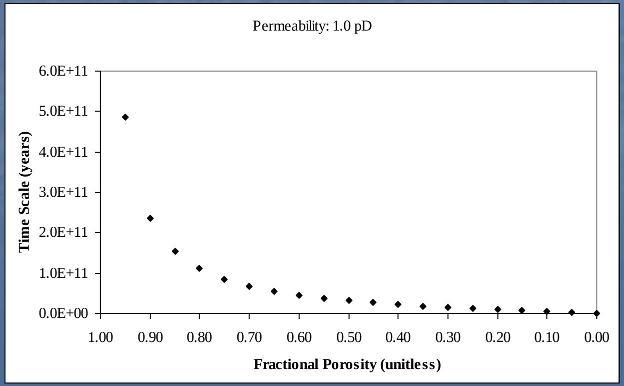

1.0 µD



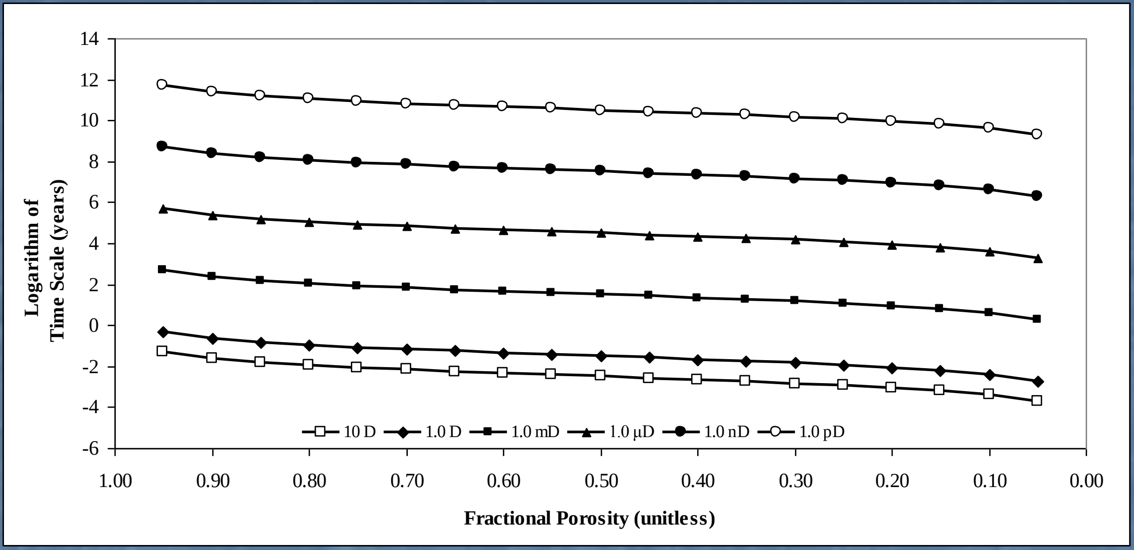

1.0 nD




1.0 pD



# Hydraulic Diffusivity Results

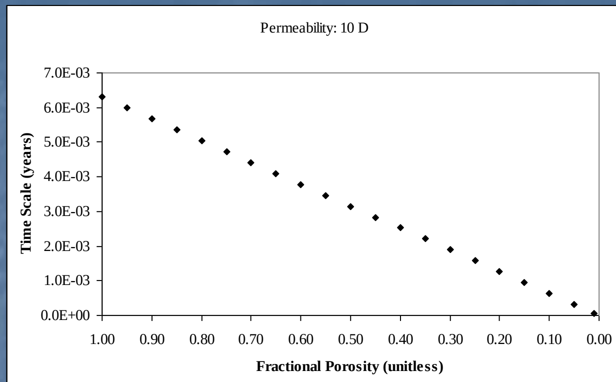



| Permeability (Darcy) | Lower Bound (Years) | Average (Years) | Upper Bound (Years) |
|---|---|---|---|
| | | | |
| 10.0 D | 1.0E-3.70 | 1.0E-2.0 | 1.0E-1.63 |
| 1.0 D | 1.0E-2.70 | 1.0E-1.0 | 1.0E-0.31 |
| 1.0 mD | 1.0E+0.30 | 1.0E+2.0 | 1.0E+2.68 |
| 1.0 µD | 1.0E+3.30 | 1.0E+5.0 | 1.0E+5.68 |
| 1.0 nD | 1.0E+6.30 | 1.0E+8.0 | 1.0E+8.68 |
| 1.0 pD | 1.0E+9.30 | 1.0E+11.0 | 1.0E+11.68 |

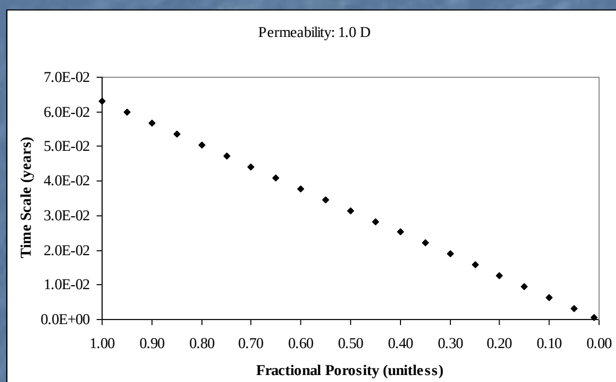
Several days to several weeks
Up to six months
Several hundred years, ~500 yrs
Several thousand years
Hundreds of millions of years
Billions of years

# Darcy's Law of Fluid Flow

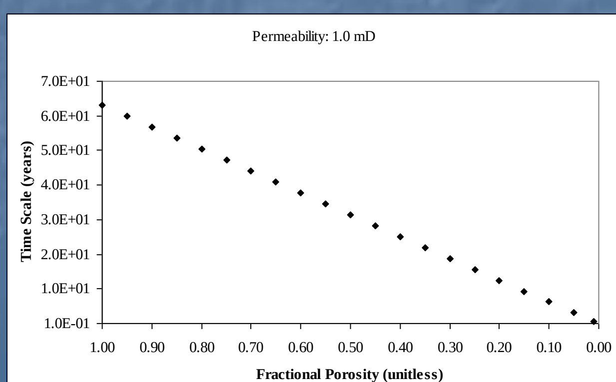
10.0 D



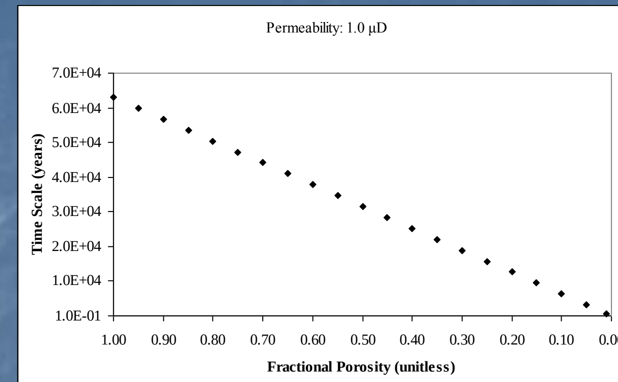

1.0 D



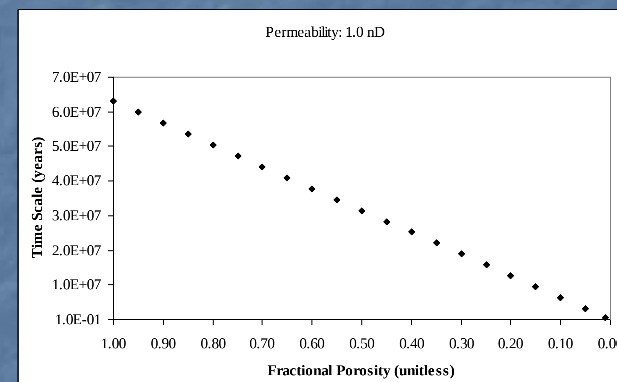

1.0 mD



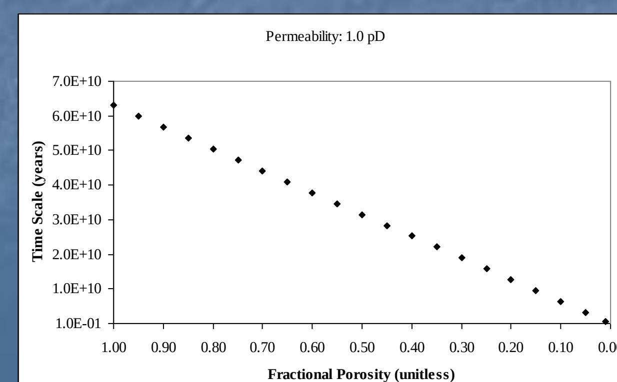

1.0 µD



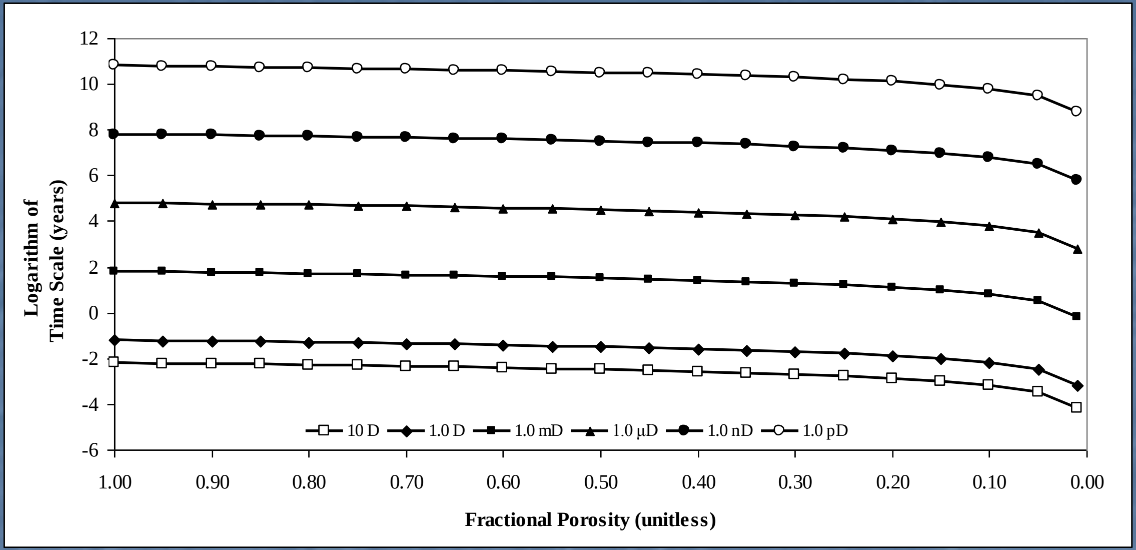

1.0 nD




1.0 pD



# Darcy's Law of Fluid Flow




| Permeability (Darcy) | Lower Bound (Years) | Average (Years) | Upper Bound (Years) | |
|---|---|---|---|---|
| | | | | |
| 10.0 D | 1.0E-3.50 | 1.0E-2.0 | 1.0E-2.22 | Several days to weeks |
| 1.0 D | 1.0E-2.50 | 1.0E-1.0 | 1.0E-1.22 | Several months |
| 1.0 mD | 1.0E+0.50 | 1.0E+2.0 | 1.0E+1.77 | 6 months up to 60 years |
| 1.0 µD | 1.0E+3.50 | 1.0E+5.0 | 1.0E+4.77 | Hundreds to several thousands of years |
| 1.0 nD | 1.0E+6.50 | 1.0E+8.0 | 1.0E+7.77 | Tens of millions of years |
| 1.0 pD | 1.0E+9.50 | 1.0E+11.0 | 1.0E+10.77 | Billions of years |

# Conclusions

- Quantification of the first-order approximations of the time scales involved in the lateral migration of sequestered $CO_2$ through a given volume of rock enables a general estimation of the containment timeframes of the sequestered gas. This study investigated these time scales for formations exhibiting permeabilities from 10.0 darcy to 1.0 picodarcy and porosities from 0.05 to 0.95.

# Conclusions (2)

- Fluid flow modeling for determining fluid migration time scales
  - Calculate generalized time scales of lateral $CO_2$ fluid migration given information about average reservoir temperature, pressure, permeability, and porosity.
  - Hydraulic diffusivity time scales exhibit hyperbolic decay contours; Darcy fluid flow time scales exhibit decreasing linear trends.
  - The orders of magnitude can be approximated as linear over a wide range of permeability-porosity values.
  - Similar order of magnitude results for diffusivity and Darcy flow suggest that these 1$^{st}$ order approximations, derived from two separate equations with different input values, yield a reliable estimation of the $CO_2$ lateral migration time scales.

# Conclusions (3)

- Formations categorized by:
  - Class I permeability may not provide adequate, long-term containment of sequestered $CO_2$ in the absence of physical trapping mechanisms. Fluid migration occurs on the order of days to weeks.
  - Class II permeability represents the most favorable scenario for injection and containment of $CO_2$. The order of magnitude for 1.0-km lateral migration of carbon dioxide through a given volume of rock ranges from several years to several thousand years.
  - Class III permeability may not represent viable injection targets without formation treatments such as hydraulic fracturing or permeability enhancement. Lateral fluid migration occurs on the order of several hundred to several hundred thousands of years.

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